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Strategic innovation in energy supply chains: Bridging efficiency and sustainability

Ehizele Dean Okoduwa * and Mohammed Lawal Giwah

Yale School of Management, New Haven Connecticut, USA.

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Abstract

The energy sector is undergoing a transformative shift as it faces growing demands for both efficiency and sustainability. Strategic innovation in energy supply chains has emerged as a solution to address these challenges. This paper explores how innovative strategies, technologies, and practices are reshaping the energy supply chain to balance operational efficiency with environmental sustainability. The integration of digital technologies, such as big data analytics, Internet of Things (IoT), and artificial intelligence, has revolutionized energy management, optimizing resource allocation, improving energy production processes, and enhancing distribution. Additionally, the push for renewable energy sources and carbon reduction practices is fostering an environment where sustainability is integrated into every stage of the supply chain, from production to consumption. The paper also discusses the key drivers of strategic innovation, including regulatory pressures, consumer demand for greener alternatives, and technological advancements. By examining case studies and current trends, the paper highlights how strategic innovation is not only improving efficiency but also driving the energy sector towards a more sustainable future. The balance between these two factors is essential for achieving long-term energy resilience and reducing the global carbon footprint. Ultimately, this discussion underscores the importance of adopting a holistic approach to energy supply chain management that aligns economic, environmental, and societal goals.

Keywords: Energy Supply Chain; Strategic Innovation; Sustainability; Efficiency; Renewable Energy; Digital Technologies

1. Introduction

Energy supply chains encompass the processes through which energy is generated, transmitted, distributed, and consumed, spanning from resource extraction, be it fossil fuels or renewable sources, to the final delivery to consumers [1, 2]. These chains are pertinent in ensuring energy reliability, security, and accessibility, which are essential for economic growth, industrialisation, and societal well-being. Historically, the efficiency of these systems has been paramount, especially given projections that global electricity demand is expected to nearly double by 2050, driven by increased electrification in buildings, industrial manufacturing, and transportation [3]. However, the increasing recognition of the environmental impact of traditional energy sources has highlighted the need for strategic innovation in energy supply chains.

The transition to low-carbon and renewable energy sources, coupled with the growing demands for sustainability, is reshaping how energy systems function. Between 2022 and 2027, global renewable capacity is anticipated to surge by almost 2,400 gigawatts (GW), an 85% acceleration compared to the previous five years, propelled by more ambitious policies in major markets [4]. Yet, integrating renewables introduces new complexities such as supply intermittency and infrastructure challenges, necessitating innovative solutions to optimise both efficiency and sustainability.

* Corresponding author: Ehizele Dean Okoduwa.

Strategic innovation in energy supply chains addresses these challenges by adopting advanced technologies and reimagining business models, regulatory frameworks, and operational practices. For instance, Denmark has successfully integrated wind energy into its national grid, with wind power supplying over 50% of the country's electricity needs in recent years. This achievement is largely attributed to advanced forecasting models, smart grid technology, and supportive policies, collectively enhancing grid stability and supply chain efficiency [5]. Similarly, China's deployment of ultra-high voltage (UHV) transmission lines has improved the efficiency of transporting renewable energy across vast distances, addressing the challenge of geographical dispersion [6].

Balancing efficiency and sustainability remains a formidable task in contemporary energy supply chains. Efficiency entails optimising energy production and distribution, minimising waste, and ensuring cost-effectiveness. Conversely, sustainability emphasises long-term environmental and social considerations, focusing on reducing greenhouse gas emissions, conserving resources, and protecting ecosystems [7]. Aligning these objectives demands a strategic approach that integrates technological advancements, regulatory support, and innovative business models. The success of future energy supply chains hinges on the ability to enhance performance while upholding environmental responsibility. Tesla's Gigafactories exemplify this balance by pioneering battery production methods that boost efficiency and reduce carbon footprints [8, 9].

Historically, efficiency and sustainability objectives have often been at odds. Fossil fuel-based power plants, for example, are cost-effective and efficient in energy production but significantly contribute to global warming, with coal-fired plants alone accounting for a substantial portion of global CO_2 emissions [10]. In contrast, renewable energy sources like wind and solar offer environmental benefits but face challenges related to efficiency and reliability due to their intermittent nature. The transition to renewable energy necessitates comprehensive planning and restructuring of energy supply chains, as these sources are often geographically dispersed and require infrastructure adaptations such as energy storage systems and upgraded transmission lines. Germany's Energiewende policy serves as a case study in balancing these factors, demonstrating both successes in renewable integration and ongoing challenges in energy security and cost management [11].

Addressing these complexities requires exploring fundamental questions shaping the future of energy supply chains. How can technological innovations enhance efficiency without compromising sustainability? What regulatory and policy frameworks are needed to support a balanced transition to low-carbon energy sources? In what ways can businesses and governments collaborate to foster resilient and adaptable energy systems? Additionally, how can energy supply chains integrate circular economy principles to minimise waste and optimise resource use? These questions highlight the need for a multidimensional approach that advances energy infrastructure while ensuring economic viability and environmental responsibility.

This paper explores strategic innovation as a means of bridge the gap between efficiency and sustainability in energy supply chains. The integration of cutting-edge technologies such as smart grids, blockchain, artificial intelligence (AI), and the Internet of Things (IoT) presents immense potential for optimising supply chain operations while supporting sustainability goals. By innovating within and across the supply chain, energy companies can enhance operational efficiency, reduce waste, and incorporate renewable energy solutions. However, achieving this balance requires a comprehensive understanding of the interdependencies between efficiency, sustainability, and innovation, as well as the trade-offs that must be managed.

2. Conceptual framework: efficiency and sustainability in energy supply chains

The transformation of energy supply chains is central to global efforts aimed at enhancing sustainability and operational efficiency. As the world intensifies its focus on combating climate change, reducing environmental impacts, and ensuring equitable access to energy resources, the interconnection between efficiency, sustainability, and strategic innovation within energy supply chains becomes increasingly critical. This section discusses the relevant concepts and examines their influence on the evolution of energy supply chains.

2.1. Efficiency in Energy Supply Chains

Efficiency in energy supply chains refers to the optimal utilisation of resources, such as raw materials, energy, and human capital, to deliver energy services cost-effectively while meeting demand [12]. This encompasses various facets such as energy production, distribution, and consumption. The International Energy Agency (IEA) describes energy efficiency as delivering the same services with less energy, thereby reducing energy demand and associated emissions [13]. Achieving high efficiency is imperative, as it leads to reduced operational costs, minimised waste, and enhanced resource utilisation, thereby yielding significant economic and environmental benefits.

2.2. Metrics used to measure efficiency in energy supply chains include:

- **Energy Conversion Efficiency (ECE):** This is a critical metric in assessing how effectively energy is transformed from one form to another in the supply chain. Higher ECE means that less energy is lost during conversion, leading to improved resource utilization and cost savings [14]. The efficiency of different energy sources varies. For instance, traditional gas turbines operate at about 40% efficiency, while advanced combined-cycle gas turbines can achieve efficiencies exceeding 60% by utilizing waste heat for additional power generation [15]. A notable example is General Electric's 826 MW 9HA.02 plants, which reported an efficiency of over 64% in December 2017, driven by advancements in additive manufacturing and combustion technology [16].
  Similarly, solar energy conversion has seen remarkable improvements. In September 2024, AIKO Solar maintained its leadership in photovoltaic efficiency by commercializing a back contact (BC) module with an impressive 24.2% efficiency and a power output of 655 W. This advancement underscores AIKO's commitment to enhancing solar energy conversion rates, setting a high benchmark in the industry [17]. Similarly, Maxeon Solar introduced its Maxeon 7 module series, achieving a notable 24.1% efficiency and a power output of 445 W. These developments highlight the rapid progression in solar module technology, contributing to more efficient and space-effective renewable energy solutions [18].
- **Supply Chain Cost Efficiency (SCCE):** This focuses on minimizing expenses across the entire energy supply chain, including procurement, transportation, storage, and distribution. Efficient supply chain management not only reduces operational costs but also enhances reliability and sustainability [19]. Research indicates that implementing energy efficiency measures can lead to significant cost savings. For instance, the U.S. Environmental Protection Agency (EPA) notes that installing ENERGY STAR-certified heating and cooling equipment can yield annual energy bill reductions of 10% to 30% [20]. Similarly, the U.S. Department of Energy highlights that addressing drafts and air leaks in buildings can prevent the loss of $200 to $400 annually, underscoring the financial benefits of efficiency upgrades [21].
  Beyond household energy efficiency, optimizing logistics operations plays a crucial role in reducing fuel consumption and transportation costs, thereby improving overall supply chain efficiency. A practical example is Tesco, the UK-based retailer, which has significantly enhanced its supply chain cost efficiency through sustainable initiatives. By electrifying its delivery fleet and shifting a portion of its freight transport to rail, Tesco has successfully reduced CO_2 emissions by over 6,000 tonnes annually [22, 23]. These measures not only contribute to environmental sustainability but also lead to considerable cost savings, demonstrating how businesses can align financial performance with sustainability goals.
- **Carbon Intensity:** This measures the amount of CO_2 emissions produced per unit of energy generated, making it a crucial indicator of an energy system's environmental impact [24]. Different energy sources exhibit varying carbon intensities, with coal-fired power plants emitting approximately 900 grams of CO_2 per kilowatt-hour (gCO_2/kWh), making them among the most carbon-intensive energy sources. In contrast, solar photovoltaic (PV) systems have a much lower carbon intensity, averaging around 50 gCO_2/kWh, highlighting the environmental benefits of transitioning to renewable energy [25]. Governments and companies worldwide are actively working to lower carbon intensity through technological innovation and investment in clean energy. For instance, in 2023, the Japanese government allocated ¥49.8 billion (approximately $450 million) under the Green Innovation Fund to support the development of next-generation solar cells, including perovskite technology. This funding aimed to accelerate research and development, with the goal of achieving public implementation by 2030 [26].

2.3. Sustainability Considerations

Sustainability in energy supply chains is defined by a balance between environmental, economic, and social dimensions, aiming to minimize adverse environmental impacts, promote social equity, and ensure long-term economic viability [27]. The Triple Bottom Line (TBL) framework, which evaluates sustainability through People (social sustainability), Planet (environmental sustainability), and Profit (economic sustainability), provides a holistic approach to achieving these goals.

- **Environmental Sustainability (Planet)**: Reducing the environmental footprint of energy supply chains is paramount. This involves adopting low-emission technologies, transitioning to renewable energy sources, and optimizing resource efficiency. A notable example is the global shift towards electric vehicles (EVs) to decrease greenhouse gas emissions in the transportation sector. According to the IEA, EV sales surpassed 10 million units in 2022, accounting for approximately 14% of global car sales, up from 9% in 2021 [28, 29]. This surge indicates a significant move away from fossil fuel dependence.

- **Social Sustainability (People):** Ensuring equitable access to affordable and reliable energy is a cornerstone of social sustainability. Energy poverty remains a major issue in many regions, hindering economic development and perpetuating social inequalities [30]. The TBL framework emphasizes the social dimension by advocating for inclusive energy access that improves livelihoods and enhances societal well-being.
  A comparative study by Carabajal et al. involved interviews with 2,658 household heads and business owners connected to mini-grids over the past five years. Participants were surveyed both before and one year after their connection, focusing on changes in gender equality, productivity, health, safety, and economic activity. The findings revealed significant improvements across all areas, including a quadrupling of median income among rural Kenyan community members [29]. This study underscores the substantial impact of decentralized renewable energy on the social and economic development of rural African communities.
- **Economic Sustainability (Profit):** Building resilient and profitable energy systems that meet current demands without compromising future needs is essential for economic sustainability. The TBL framework recognizes that financial viability is crucial for long-term sustainability. Investments in renewable energy not only contribute to environmental goals but also offer economic benefits. A study analyzing companies in the renewable sector found that such investments improved profitability and market valuation, particularly during economic recovery phases. The research indicated that investments and spending on research and development positively affect profitability indicators such as earnings before interest, taxes, depreciation, and amortization (EBITDA), earnings before interest and tax (EBIT), net income, and return on investment [31]. These findings suggest that financial performance in the renewable energy sector is enhanced by strategic investments, especially during periods of economic recovery. For instance, larger firms like EDP (Energias de Portugal) have experienced employment growth, highlighting the sector's financial resilience. In 2020, EDP reported a total installed capacity of 24 gigawatts (GW), with 79% corresponding to renewable energies. EDP Renováveis, the subsidiary of EDP Group operating in wind and solar power production, reached an installed wind capacity of 12.2 GW in 2020, registering a growth of 0.8 GW (7%) compared to the previous year [32]. This expansion reflects the company's commitment to renewable energy and its positive impact on employment within the sector.

2.4. The Nexus between Efficiency and Sustainability

Enhancing efficiency in the energy supply chains often yields sustainability benefits, notably through the reduction of carbon emissions. A prime example is the implementation of Combined Heat and Power (CHP) systems, which simultaneously generate electricity and useful heat from a single energy source. These systems can achieve fuel efficiencies up to 90%, significantly lowering carbon emissions and operational costs. For instance, the McAlpine Creek Wastewater Management Facility in North Carolina installed a 1 MW CHP system, resulting in annual savings of $300,000 in energy costs and a substantial reduction in greenhouse gas emissions [33]. However, the pursuit of efficiency can sometimes conflict with sustainability objectives. For example, while large-scale hydropower projects are efficient in energy production, they can lead to ecological disruptions and displacement of communities, posing challenges to environmental and social sustainability.

3. Challenges in energy supply chains

Energy supply chains are fundamental to meeting the world's growing demand for energy while transitioning to sustainable sources. The strategic innovation in energy supply chains, particularly focusing on bridging the gap between efficiency and sustainability, presents various challenges. These challenges stem from both efficiency-driven factors and sustainability-driven concerns, which together shape the landscape of energy production, distribution, and consumption. In addressing these challenges, it is crucial to consider the economic, technological, social, and policy factors that underpin energy systems globally.

3.1. Efficiency-Driven Challenges

Energy providers are under immense pressure to achieve cost reductions and operational efficiency while maintaining a reliable and continuous energy supply. This section outlines the key challenges that hinder efficiency in energy supply chains, which are vital for ensuring uninterrupted services to end-users.

3.1.1. Cost Reduction Pressures and Operational Efficiency

In today's competitive energy market, providers face pressure to minimize operational costs while ensuring effective supply chains. This challenge is intensified by the necessity for investments in infrastructure, innovation, and digitalization. The IEA reported in 2020 that global energy investment was projected to decline by 18%, reflecting the financial constraints within the industry [34]. The trade-offs between short-term cost reductions and long-term infrastructural investments can lead to challenges such as a lack of innovation and stagnant operational practices. The IEA's World Energy Investment 2020 report highlighted that lower expected electricity demand and prices were likely to delay capital spending in coal-fired plants, indicating how cost pressures can postpone essential infrastructure projects [35].

Moreover, the pressure to reduce costs often results in delayed or underfunded infrastructure projects. The IEA emphasized that energy infrastructure is long-lived, and investment in fixed infrastructure should consider the long term. Electrification of end uses will reshape demand, necessitating modernized infrastructure to accommodate renewable energy sources and enhance grid resilience [36].

3.1.2. Infrastructure Constraints

The energy supply chain faces challenges due to aging infrastructure, much of which was designed in the mid-20th century to support fossil fuel-based power generation. These outdated systems are often ill-equipped to handle the increasing demand for electricity and the integration of renewable energy sources such as wind and solar power. The International Renewable Energy Agency (IRENA) emphasizes that modernizing existing infrastructure is essential to accommodate renewable power, necessitating grid reinforcement and expansion both on land and sea [37].

Energy storage solutions are also underdeveloped, posing challenges in balancing the intermittent nature of renewable energy sources. While advancements in battery technology have been made, current storage capacities are insufficient to support widespread renewable energy adoption. The U.S. Department of Energy's 2020 Energy Storage Market Report highlights that, despite projections, the European electric-car market exceeded China's for the first time in 2020, indicating growth related to sustained policies and subsidies [38].

Modernizing energy infrastructure is capital-intensive and requires coordinated efforts among governments, private companies, and utilities. The World Bank notes that constrained fiscal space and lack of access to finance make costly upfront investments in energy efficiency and renewable energy out of reach for developing countries [39].

3.2. Technological Limitations in Traditional Energy Systems

Traditional energy systems were designed to operate around fossil fuel-based generation methods, which are predictable and can be ramped up or down easily. In contrast, renewable energy sources like solar and wind power are intermittent and less predictable, creating challenges for grid operators trying to balance supply and demand in real time.

The technological limitations of traditional energy systems make it difficult to integrate renewable energy sources into the existing grid infrastructure. Energy systems were not designed to accommodate the distributed nature of renewable energy generation, nor were they built to handle the complexity of managing variable energy inputs. Consequently, there are difficulties in matching supply to demand efficiently, which can result in power outages, energy wastage, and inefficiencies within the energy supply chain [40, 41].

Additionally, while renewable energy technologies have significantly advanced in recent years, their integration into the grid requires substantial investments in smart grid technologies, demand response systems, and flexible energy storage solutions. These technological hurdles present significant challenges for energy providers striving for greater efficiency.

3.3. Economic and Financial Hurdles

Upgrading energy infrastructure and adopting innovative technologies is financially demanding for energy providers, particularly in developing countries. The high capital costs associated with modernizing grids, integrating renewable energy sources, and investing in advanced energy storage solutions can be prohibitive. Developing economies, which account for two-thirds of the world's population, receive only one-fifth of global clean energy investments. Annual investments across all parts of the energy sector in these regions have declined by around 20% since 2016, partly due to persistent challenges in mobilizing finance for clean energy projects [42].

The financial risks associated with emerging energy technologies, such as carbon capture and storage (CCS) and advanced nuclear power, further complicate investment decisions. CCS projects, for instance, are not yet considered investable due to uncertainties in project costs and technical performance. Consistent demonstration at a commercial scale is necessary to verify deployment and mitigation costs, proving CCS as an effective abatement option [43]. Similarly, while nuclear power can contribute to decarbonizing the energy sector, its economic viability is influenced by high capital costs and long development timelines. Without action, nuclear power in advanced economies could decline by two-thirds by 2040, impacting costs, emissions, and electricity security [44].

Consequently, energy providers may be reluctant to invest in such technologies without government incentives, long-term policies, or clear financial models. Addressing these economic and financial hurdles is essential for advancing energy infrastructure and technology adoption, ensuring a sustainable and resilient energy future.

3.3.1. Sustainability-Driven Challenges

While efficiency remains a significant concern for energy supply chains, the transition towards sustainability introduces a host of additional challenges. These challenges revolve around reducing dependence on fossil fuels, mitigating environmental impacts, and addressing social equity issues as energy systems evolve.

Dependence on Fossil Fuels

The global energy sector continues to rely heavily on fossil fuels, with coal, oil, and natural gas accounting for approximately 80% of primary energy consumption [45]. This dependence is particularly pronounced in emerging economies, where fossil fuels are often favored due to their established infrastructure and perceived affordability.

Fossil fuel subsidies play a role in perpetuating this reliance. In 2022, these subsidies reached a record $7 trillion, equivalent to 7.1% of global GDP [46]. Such financial support can create market distortions, making it challenging for renewable energy technologies to compete on an equal footing. The IEA has highlighted that removing inefficient fossil fuel subsidies could positively impact energy markets, government budgets, and efforts to address climate change [47].

Transitioning away from fossil fuels presents substantial challenges, especially for countries lacking the financial resources to invest in renewable energy infrastructure. The high capital costs associated with clean energy technologies and the need for capacity-building are significant barriers. The IRENA emphasizes that subsidies for clean and renewable energy can improve the efficiency of capital allocation across the energy sector, aiding in the transition to sustainable energy systems [48].

3.3.2. Carbon Emissions and Environmental Concerns

The energy sector is a major contributor to global greenhouse gas emissions, primarily due to its reliance on fossil fuel-based energy generation. This contribution underscores the urgency for the sector to reduce carbon emissions to meet international climate targets, such as those outlined in the Paris Agreement. The Paris Agreement aims to limit global temperature rise to well below 2°C, preferably to 1.5°C, above pre-industrial levels, necessitating substantial emission reductions from all sectors, including energy [49].

Transitioning to low-carbon energy alternatives presents both technological and economic challenges. Renewable energy sources like wind and solar are intermittent, making their integration into existing grid systems complex. Additionally, while energy storage technologies are advancing, they have not yet achieved the reliability required to consistently balance supply and demand when renewable generation fluctuates. The IEA emphasizes that overcoming these barriers is crucial for meeting climate goals, highlighting the need for rapid deployment of existing clean energy solutions and significant advancements in low-carbon technologies [50]. Addressing the environmental impacts of existing energy infrastructure is also imperative. For example, coal-fired power plants are among the largest sources of CO_2 emissions, and phasing them out while ensuring a stable energy supply remains a challenge. Moreover, the extraction and transportation of fossil fuels, such as oil and gas, can lead to environmental degradation, including habitat destruction and water contamination. The International Monetary Fund (IMF) notes that despite a growing global consensus on the need for decarbonization, obstacles such as technological limitations and financial constraints continue to impede progress toward net-zero emissions [51].

3.3.3. Regulatory and Policy Barriers

Regulatory and policy barriers are notable challenges to the transition toward sustainable energy systems. Inconsistent policies, insufficient incentives for renewable energy adoption, and the persistence of fossil fuel subsidies often undermine efforts to reduce the carbon footprint of energy supply chains. This regulatory fragmentation creates uncertainty for energy providers, complicating long-term planning and investment [52].

Moreover, geopolitical factors, such as global competition for energy resources, further complicate the energy transition. Political instability in oil-producing regions often lead to price volatility and disrupt supply chains, making it more challenging for countries to commit to renewable energy alternatives.

3.3.4. The Trade-Off Between Efficiency and Sustainability

Energy supply chains are at the intersection of the global demand for energy and the imperative for sustainable development. The ongoing challenges in these supply chains are complex, involving economic, technological, environmental, and geopolitical factors. One of the most critical dilemmas faced by energy supply chains is the trade-off between efficiency and sustainability. The quest for efficiency often emphasizes cost-cutting, streamlined operations, and maximized output, whereas sustainability mandates a shift towards low-carbon alternatives, resource conservation, and the minimization of environmental footprints. This section discusses the challenges that arise from this trade-off and examines how these competing priorities impact energy supply chains.

Conflicting Priorities: Efficiency vs. Sustainability

The energy supply chain is fundamentally challenged by the need to balance operational efficiency with sustainability goals. Efficiency in energy supply chains often focuses on minimizing costs, improving resource utilization, and optimizing logistical operations to ensure that energy products reach consumers at the lowest possible cost. This includes strategies such as fuel optimization, just-in-time inventory management, and the reduction of operational redundancies.

However, sustainability introduces complexities. Renewable energy sources, while essential for reducing greenhouse gas emissions and mitigating climate change, often come with higher upfront costs and require long-term investment [53, 54]. For instance, solar and wind technologies, although increasingly cost-competitive, often require initial capital investments and new infrastructure that may not align with the short-term cost-reduction goals of energy firms. Moreover, many sustainable technologies require different supply chain processes, such as sourcing critical materials like lithium, cobalt, and rare earth metals, which introduces both cost and logistical complexities [54].

In this environment, energy companies must navigate the balancing act of meeting short-term profitability objectives while simultaneously investing in sustainability initiatives. Achieving this balance requires a strategic approach that includes gradual transitions, technological innovations, and policy support that incentivize low-carbon investments without undermining operational efficiency.

Slow Adoption of Innovative Technologies

While technological innovations hold the potential to revolutionize energy supply chains, the pace of their adoption has been slow due to several barriers. Technologies such as smart grids, blockchain, Artificial Intelligence (AI), and the Internet of Things (IoT) promise substantial benefits in improving the efficiency, reliability, and transparency of energy systems. For instance, smart grids enable real-time monitoring of energy flow, allowing utilities to dynamically balance supply and demand, while blockchain can improve transparency and reduce fraud in energy transactions [55, 56].

However, integrating these technologies into existing systems is not without challenges. Traditional energy companies, which often operate using established, centralized systems, may face resistance when transitioning to decentralized, digital-first models. This resistance stems from several factors, including the complexity of integrating new technologies into legacy infrastructure, high initial costs, and a lack of skilled workforce to manage these advanced systems [57, 58, 59]. Moreover, some stakeholders may be reluctant to adopt these technologies due to concerns over cybersecurity, privacy, and regulatory uncertainties [58].

Despite these challenges, there are successful examples of technological adoption in energy supply chains. For instance, the implementation of smart grids in countries like Denmark has demonstrated the potential of digital technologies in improving grid efficiency and integrating renewable energy sources [6].

- **Geopolitical and Supply Chain Risks**

Energy supply chains are increasingly influenced by geopolitical risks, especially as the world transitions to renewable energy. The production of renewable energy technologies, such as solar panels, wind turbines, and EV batteries, relies heavily on minerals like lithium, cobalt, and nickel. These minerals are primarily sourced from a handful of countries, many of which are located in politically unstable regions. For example, approximately 60% of global cobalt production comes from the Democratic Republic of the Congo, where political instability, child labour, and human rights violations are pervasive [60, 61]. The reliance on these minerals creates vulnerabilities in the global energy supply chain, as geopolitical tensions, trade restrictions, and natural disasters can disrupt supply.

4. Strategic innovations in energy supply chains

Energy supply chains are essential in meeting the ever-growing demand for energy while ensuring environmental sustainability. The integration of strategic innovations is increasingly vital in transforming these chains to be more efficient, sustainable, and flexible. This section several strategic innovations that are driving the evolution of energy supply chains towards enhanced performance and environmental responsibility.

4.1. Technological Advancements and Digitalisation

The fusion of new technologies with energy systems is enabling considerable improvements in efficiency, sustainability, and resilience across energy supply chains. From smart grids to blockchain, technological advancements are offering novel solutions to long-standing challenges in energy management.

4.1.1. Smart Grids and Decentralised Energy Systems

Smart grids are transforming the way energy is generated, distributed, and consumed. These grids use information technology to monitor and manage energy flow, enabling more efficient and reliable energy systems. With decentralised energy production, such as solar panels and wind turbines, being integrated into the grid, energy production becomes more flexible and localized [62]. Smart grids can detect outages, prevent energy theft, and balance supply with demand in real time. For instance, the U.S. Department of Energy's Smart Grid Investment Grant (SGIG) program invested $7.9 billion in smart grid technologies, leading to significant reductions in outage times and improved grid reliability [63].

4.1.2. Artificial Intelligence (AI) and Big Data Analytics

AI and Big Data Analytics are revolutionizing energy systems by enabling predictive maintenance, accurate demand forecasting, and optimized grid management. By analyzing extensive datasets, AI algorithms can identify consumption patterns, predict future energy needs, and detect anomalies, facilitating proactive maintenance and efficient resource allocation [64]. AI-powered predictive maintenance utilizes machine learning models to analyze historical and real-time sensor data, identifying potential equipment failures before they occur [65]. This approach enhances operational efficiency and reduces unplanned downtime. For instance, Delfos Energy implemented AI modules in wind farms, resulting in an 18% reduction in lost energy due to downtimes [66].

Notably, AI enhances grid management by analyzing data to predict and respond to fluctuations in energy supply and demand [67]. This capability is essential for integrating renewable energy sources, which can be variable.

4.1.3. Blockchain for Energy Transactions

Blockchain technology is revolutionizing energy transactions by providing a secure, transparent, and decentralized platform for verifying and recording energy exchanges [68]. By eliminating intermediaries, blockchain enhances trust between buyers and sellers, reduces transaction costs, and promotes efficient energy markets. A notable example is Powerledger, an Australian-based company that has developed a blockchain-enabled peer-to-peer (P2P) energy trading platform. This platform allows consumers to trade renewable energy directly with one another, fostering local energy markets and reducing reliance on centralized utilities. In an Australian case study, Powerledger's platform was implemented in a community of 300 participants, including consumers and prosumers with solar photovoltaic systems [69]. The results demonstrated significant benefits, such as financial savings for prosumers and a substantial decrease in dependence on the main power grid, leading to enhanced grid stability and efficiency. Implementing blockchain for energy transactions can reduce operational costs by up to 30% by streamlining processes and reducing the need for intermediaries [70].

4.1.4. Internet of Things (IoT) and Automation

IoT is revolutionizing energy management by enabling real-time data collection, monitoring, and decision-making across the energy supply chain. IoT-enabled sensors provide detailed insights into energy consumption patterns in homes, commercial buildings, and industrial facilities, facilitating the identification of inefficiencies and opportunities for optimization [71].

In energy distribution networks, IoT-driven automation enhances grid stability and reduces energy losses. A notable example of IoT application in energy management is the deployment of smart meters. In Spain, EDP HC ENERGÍA has installed over 600,000 smart meters in households, allowing customers to monitor their real-time energy usage and adjust consumption accordingly, leading to cost savings and reduced emissions [72]. Similarly, Barcelona has implemented 19,500 smart meters to monitor and optimize energy consumption in targeted areas, contributing to improved energy efficiency [73].

The global IoT energy management market reflects the growing adoption of these technologies. It was Valued at USD 61.02 billion in 2022, the market is projected to reach USD 222.56 billion by 2030, exhibiting a compound annual growth rate (CAGR) of 17.8% [74]. This growth underscores the increasing recognition of IoT's potential to enhance energy efficiency and sustainability.

Research indicates that IoT technology can reduce energy consumption by up to 30% and operating expenses by 20% in smart buildings [75]. These savings are achieved through real-time monitoring and control of energy usage, predictive maintenance, and fault detection. For instance, IoT devices can detect anomalies in equipment performance, enabling proactive maintenance and preventing costly breakdowns.

In the industrial sector, IoT energy management solutions have been instrumental in optimizing energy usage. Companies have implemented IoT-driven systems to monitor machinery operations, leading to significant energy savings and improved operational efficiency [76]. These systems provide real-time data on energy consumption, allowing for informed decision-making and strategic planning.

4.1.5. Virtual Power Plants (VPPs) for Grid Stability

VPPs are revolutionizing energy management by aggregating Distributed Energy Resources (DERs) such as EVs, home batteries, and renewable energy systems to function collectively as a single power plant [77]. This aggregation enhances grid stability, optimizes energy distribution, and improves demand-response efficiency. A prominent example is Octopus Energy's 'Intelligent Octopus' initiative in the United Kingdom. Launched in 2021, this program manages over 100 megawatts (MW) of EV charging power, surpassing the capacity of the largest standalone battery on the UK grid. By incentivizing EV owners to charge during periods of abundant renewable energy, the initiative not only balances the grid but also offers cost savings to consumers. Participants benefit from reduced electricity rates, with charging costs dropping to approximately 3 pence per mile, making sustainable energy consumption more affordable [78].

In the United States, Octopus Energy has extended its VPP model to Texas through the 'Intelligent Octopus for Home Batteries' program. This enables homeowners to utilize their home battery systems to support grid stability. By automatically charging batteries during periods of surplus renewable energy and discharging during peak demand, participants receive a 50% discount on their energy rates [79]. This approach not only provides financial benefits to consumers but also contributes to a more resilient and efficient energy grid.

4.2. Business Model Innovations

In addition to technological innovations, new business models are emerging in the energy supply chain, offering alternative ways of delivering energy services that are more consumer-driven, flexible, and sustainable.

4.2.1. Energy-as-a-Service (EaaS) and Decentralised Markets

The traditional centralized energy supply model is evolving into more flexible, consumer-centric frameworks, notably through Energy-as-a-Service (EaaS) models. In this paradigm, consumers pay for energy services rather than the energy itself, enabling tailored solutions such as solar installations, battery storage, and smart energy management systems. This shift fosters decentralized energy markets, granting consumers greater control over their energy usage, often through subscription-based models [80]. A practical example of EaaS implementation is Con Edison's initiatives in the United States. In 2018, Con Edison launched a program to distribute LED light bulbs to its lower-income customers via community food banks, aiming to enhance energy efficiency among underserved populations [81]. Additionally, Con Edison has been recognized for using smart meters to improve programs that incentivize residential customers to reduce usage during peak demand times, thereby optimizing energy consumption and providing cost savings [82].

Another notable case is Signify's "Light-as-a-Service" offering, which allows businesses to adopt energy-efficient lighting solutions without the high initial costs associated with system acquisition and maintenance. This model has been implemented in Nexans's Swiss facility in Cortaillod and over 10 other sites globally, demonstrating the scalability and effectiveness of EaaS in promoting sustainable practices [83].

The EaaS model not only provides financial benefits by reducing upfront capital expenditures but also aligns with global sustainability goals by promoting the adoption of energy-efficient technologies and renewable energy sources. As the energy landscape continues to evolve, EaaS offers a viable pathway for consumers and businesses to achieve greater energy autonomy and efficiency.

4.2.2. Peer-to-Peer (P2P) Energy Trading

P2P energy trading enables individuals and businesses to directly exchange surplus energy generated from renewable sources, therefore, fostering decentralized energy systems and enhancing community self-sufficiency [84]. This model provides financial incentives for energy producers and promotes the adoption of renewable energy. In Australia, the AGL Virtual Trial of Peer-to-Peer Energy Trading, conducted between 2017 and 2018, simulated P2P energy trades using data from 68 residential customers in Carrum Downs, Victoria. The trial aimed to identify and value P2P energy trades, assess the applicability of distributed ledger technology, and analyze the results. This initiative marked a significant step toward decentralized energy systems in the region [85].

Similarly, the RENeW Nexus project in Fremantle, Western Australia, launched in 2018, involved 18 households participating in a blockchain-based P2P solar energy trading trial. The project demonstrated the technical feasibility of localized energy markets and highlighted the potential of such models to enhance energy system efficiency [86]. These Australian case studies underscore the viability of P2P energy trading platforms in promoting renewable energy adoption and empowering consumers.

4.3. Policy and Regulatory Innovations

The rapid transformation of the energy landscape requires innovative policies and regulations that foster the adoption of sustainable energy solutions while ensuring grid stability and energy security.

4.3.1. Carbon Pricing and Green Incentives

Carbon pricing serves as a policy instrument, compelling businesses to internalize the environmental costs of their greenhouse gas emissions by assigning a monetary value to carbon output [87]. This strategy not only incentivizes the reduction of emissions but also stimulates investment in low-carbon technologies, including renewable energy, energy efficiency enhancements, and carbon capture solutions. Complementing carbon pricing, governments worldwide have instituted green incentives, such as tax credits, grants, and feed-in tariffs, to further promote the adoption of clean energy technologies. The European Union Emissions Trading System (EU ETS), operational since 2005, exemplifies a large-scale implementation of carbon pricing. As the world's first multinational cap-and-trade program, the EU ETS encompasses approximately 45% of the EU's carbon emissions, targeting sectors like power generation and manufacturing. Between 2008 and 2016, the EU ETS was instrumental in abating about 1.2 billion tons of CO_2 emissions, equating to a 3.8% reduction compared to a scenario without such a market. This reduction represents nearly half of the EU's commitments under the Kyoto Protocol. Moreover, the EU ETS has spurred innovation, leading to a 10% increase in low-carbon patenting among regulated firms, thereby fostering the development of sustainable technologies [88, 89].

In the United States, federal support for renewable energy has amplified the country's clean energy landscape. From fiscal years 2016 to 2022, federal subsidies for renewable energy sources, including biofuels, wind, and solar, more than doubled, escalating from $7.4 billion to $15.6 billion. This financial backing has been instrumental in driving the growth of renewable energy sectors, making sustainable energy solutions more accessible and cost-effective. Additionally, the Energy Efficiency and Renewable Energy (EERE) funding has been transformative, with approximately 3.1 million Americans employed in renewable energy and energy efficiency jobs as of 2022. Notably, energy efficiency sectors added over 50,000 jobs, employing more than 2.2 million workers, while the battery electric vehicle sector experienced a 27% job growth year-over-year [90. 91].

These case studies from the EU and the U.S. illustrate the efficacy of carbon pricing and green incentives in driving substantial reductions in greenhouse gas emissions, fostering innovation in low-carbon technologies, and stimulating economic growth through job creation in the renewable energy sector.

4.3.2. Public-Private Partnerships (PPPs) in Energy Transition

PPPs have emerged as a good strategy in accelerating the global energy transition, fostering collaboration between governments, private enterprises, and research institutions to implement sustainable energy solutions. These alliances leverage the strengths of each sector, mitigating financial risks and expediting the deployment of clean energy infrastructure. India's ambitious renewable energy goals exemplify the impact of effective PPPs. Initiated in 2010, the National Solar Mission set a target of achieving 100 gigawatts (GW) of solar capacity by 2022. Although the country reached approximately 70.10 GW by June 2023, with an additional 55.60 GW under development, the progress underscores the significant role of PPPs in this endeavor. Notably, solar parks developed and operated by private entities are projected to contribute 40% of this target, highlighting the private sector's substantial involvement in scaling up solar infrastructure [92, 93].

PPPs are instrumental in advancing energy transitions worldwide. In South Africa, the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has attracted significant private investment, leading to the development of numerous renewable energy projects and contributing to the country's energy diversification and sustainability objectives [94].

4.3.3. Standardisation and Regulatory Adaptability

Standardization and regulatory adaptability are vital in fostering innovation and investment within the clean energy sector. Clear and consistent regulations provide market participants with the confidence to invest in and deploy new technologies, minimizing legal and operational uncertainties. Conversely, adaptable regulatory frameworks can accommodate emerging technologies and evolving market conditions, thereby promoting continuous innovation in energy supply chains.

The European Union's 'Clean Energy for All Europeans' package exemplifies a comprehensive approach to standardization in the energy market. This legislative package adopted in May 2019 comprises eight legislative acts focusing on areas such as the energy performance of buildings, renewable energy, energy efficiency, governance, and electricity market design. Its primary objective is to create a more integrated, competitive, and sustainable energy market across EU member states by establishing a unified set of rules and standards [95]. This harmonization facilitates cross-border energy trade, enhances grid stability, and encourages investments in renewable energy projects by providing a predictable regulatory environment.

An important component of this package is the updated electricity market design, which aims to integrate an increasing share of renewable energy sources and new technologies in a flexible manner, without compromising the security of supply. This design empowers consumers to actively participate in the energy market, reflecting the evolving dynamics of energy production and consumption [96].

5. Conclusion

Strategic innovation in energy supply chains is imperative to bridge the gap between operational efficiency and sustainability. Through the integration of advanced technologies, energy supply chains can be optimized to reduce waste, enhance productivity, and lower carbon emissions. The findings of this paper highlight that while the energy sector faces several challenges, strategic innovation offers viable solutions for overcoming these obstacles. Notably, the adoption of sustainable practices and the transition to clean energy sources are paramount in ensuring the long-term viability of energy systems.

To foster continued progress, it is recommended that policymakers and industry leaders prioritise investments in research and development of green technologies, as well as establish frameworks that support collaboration between stakeholders across the energy value chain. Additionally, regulatory policies should incentivize the adoption of sustainable practices while providing a clear roadmap for the integration of innovative solutions. Ultimately, achieving an optimal balance between efficiency and sustainability in energy supply chains will require a holistic approach that combines technological advancements, policy support, and industry collaboration.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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